

## ***Final Summary of Research***

**NASA Grant NAG5-11253 to the University of South Carolina**  
**An Assessment of Global Organic Carbon Flux Along Continental Margins**

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### **Research Objective**

This project was designed to use real-time and historical SeaWiFS and AVHRR data, and real-time MODIS data in order to estimate the global vertical carbon flux along continental margins. This required construction of an empirical model relating surface ocean color and physical variables like temperature and wind to vertical settling flux at sites co-located with sediment trap observations (Santa Barbara Basin, Cariaco Basin, Gulf of California, Hawaii, and Bermuda, etc), and application of the model to imagery in order to obtain spatially-weighted estimates.

### **Accomplishments-to-Date**

Over the course of this study, we have implemented the software to generate and process the latest release (version 4) of the global SeaWiFS data. We have compared these new satellite data to concurrent field observations collected in both Santa Barbara Basin and Cariaco Basin, and validated an improved Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997). Better understanding has been gained in how surface and export production in the Cariaco Basin respond to seasonal and interannual variations in regional meteorological, hydrographic and circulation conditions.

While testing and validating the VGPM using CARIACO data, we have initiated implementation of global carbon flux assessments based on remote sensing data. Using SeaWiFS monthly chlorophyll, PAR and AVHRR SST data, we have calculated global primary productivity with the improved VGPM construct and parameterizations. Our research has been driven by two fundamental questions: 1) *How good are global carbon assessments if continental margins are omitted?* and 2) *How much POC reaches ocean depths where it may be considered "sequestered"?*

#### **A. Coastal Upwelling and Carbon Fluxes in the Cariaco Basin**

Monthly hydrographic observations, phytoplankton biomass and primary production estimates, bio-optical observations, and particulate organic carbon flux measurements have been collected at 10.5°N, 64.67°W within the Cariaco Basin, off Venezuela, since November 1995. These data were combined with a time series of SeaWiFS, AVHRR, and ERS/QuikScat data to examine the spatial extent of a cold coastal upwelling plume and the phytoplankton bloom associated with it. The seasonal upwelling cycle is directly linked to the intensity of the trade winds, with sea surface temperature (SST) changes lagging the wind by 1-2 weeks. The seasonal cycle of most properties is punctuated by

transient phenomena, some of which caused subsurface ventilation and high primary production events. Integrated primary production ranged from 650, 574, and 593  $\text{gC m}^{-2} \text{y}^{-1}$  in 1996, 1997, and 2001, respectively, to 372, 484, and 448  $\text{gC m}^{-2} \text{y}^{-1}$  respectively in 1998, 1999, and 2000. The Rutgers Vertical Generalized Production Model (VGPM) was modified to reflect an increase in assimilation number ( $\text{PB}^{\text{opt}}$ ) with SST at the Cariaco time series station, because the original VGPM formulation suggested inhibition of primary production at  $\text{SST} > 21^\circ\text{C}$ . Trap observations showed that between 9-10  $\text{gC m}^{-2} \text{y}^{-1}$  were delivered to the bottom at the Cariaco time series station, i.e.  $\sim 1.33\%$  of surface primary productivity. Annual particulate organic carbon flux to the bottom over the area of the Cariaco Basin (waters  $> 100 \text{ m}$ ), estimated using SeaWiFS and AVHRR variable inputs and the updated VGPM, ranged from  $6.77 \times 10^{10}$  to  $7.61 \times 10^{10} \text{ gC}$ . These are likely underestimates due to lack of bathymetric corrections to flux.

The results of this study help advance our understanding of how satellites may be combined with *in situ* observations to assess the fate of carbon in the ocean. Time series like that in Cariaco Basin are critical to make progress in this scientific endeavor. Some of the major conclusions that may be drawn from our research are as follows:

1. The seasonal upwelling cycle is directly linked to the intensity of the Trade Winds, with sea surface temperature (SST) changes lagging the wind by 1-2 weeks.
2. The seasonal cycle of most properties is punctuated by transient phenomena, some of which caused subsurface ventilation and also high primary production events.
3. Integrated primary production at the CARIACO station is high, with values typically exceeding  $550 \text{ gC m}^{-2} \text{y}^{-1}$ . Occasional lower production years ( $< 400 \text{ gC m}^{-2} \text{y}^{-1}$ ) may be associated with ENSO events.
4. There are still issues with the accuracy of the SeaWiFS chlorophyll-a concentration product, even after reprocessing version 4. Typically, SeaWiFS chlorophyll-a tended to overestimate *in situ* observations at the CARIACO station, particularly during periods of low chlorophyll. We speculate that this may be the result of local high elevations of colored dissolved organic matter associated with river discharge. The question of whether upwelling waters contain CDOM generated in remote locations remains unresolved.
5. The Rutgers Vertical Generalized Production Model (VGPM) underestimated primary production at high tropical sea surface temperatures ( $\text{SST} > 21^\circ\text{C}$ ), and thus required a new local relationship between assimilation number ( $\text{PB}^{\text{opt}}$ ) and SST. Our observations are consistent with those of Gong et al. (2000) for the subtropical East China Sea. The significance of this observation is that previous estimates of global primary productivity using satellites likely underestimate the contribution of the tropics. Much productivity may occur at high temperature and low chlorophyll concentration over large areas of the tropical and subtropical oceans. Clearly, an inaccurate parameterization of the photoadaptive parameter(s) in such bio-optical productivity models would lead to large errors in global production estimates.
6. Regional variability in phytoplankton biomass and primary productivity do not necessarily track global patterns in response to ENSO events; for example

Behrenfeld et al. (2001) reported that both global ocean chlorophyll and primary productivity increased between 1997 and 1998 over an ENSO event. Both these quantities decreased at the CARIACO station and in the southeastern Caribbean Sea.

7. Trap observations show that between  $9\text{--}10 \text{ gC m}^{-2} \text{ y}^{-1}$  are delivered to the bottom at the CARIACO station, i.e.  $\sim 1.33\%$  of surface primary productivity. Annual particulate organic carbon flux to the bottom over the area of the Cariaco Basin (waters  $>100 \text{ m}$ ), estimated using SeaWiFS and AVHRR variable inputs and the updated VGPM, ranged from  $6.77 \times 10^{10}$  to  $7.61 \times 10^{10} \text{ gC}$  (likely underestimates due to lack of bathymetric corrections to flux).

### **B. Carbon Fluxes on Continental Margins and the Global Carbon Cycle**

We used modern satellite data at  $9 \text{ km}$  resolution to estimate global POC fluxes to the sea floor everywhere where depths exceeded  $50 \text{ m}$ . We computed monthly mean global ocean net primary production (NPP) for 1998 through 2001 using the VGPM. Net production is an estimate of the total carbon fixed by photosynthesis minus respiration in the euphotic zone. Sea surface temperature (SST) was derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite sensor, and chlorophyll and Photosynthetically Active Radiation (PAR) data were derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Sinking POC flux to the ocean's bottom was computed using an exponential decay model, with flux projected to the ocean bottom as defined by a global bathymetry database. Continental margins were defined as regions between  $50$  and  $2,000 \text{ m}$  depth.

Over the global ocean, annual net primary production averaged  $47.91 \text{ Pg C}$  (1998–2001), varying less than  $\pm 2\%$  from year to year. We estimated an average of  $8.99 \text{ Pg C y}^{-1}$  NPP over continental margins (areas where the bottom lies between  $50$  and  $2,000 \text{ m}$ ), with interannual variability  $< \pm 1\%$ . Previous estimates (Behrenfeld et al., 2001; Gregg et al., 2003) for the deep ocean derived with the VGPM using the Coastal Zone Color Scanner (CZCS), SeaWiFS, and AVHRR satellite data are similar to those obtained in this study ( $38.92 \text{ Pg C y}^{-1}$  NPP) within about  $20\%$ . The differences are well within variation associated with disparity in methods used to process the SeaWiFS data.

The four-year average global POC flux to the bottom was  $0.93 \text{ Pg C y}^{-1}$  ( $< \pm 1\%$  interannual variation). In the deep ocean, the total amount of POC deposited on the sea floor at depths  $>2,000 \text{ m}$  was  $0.31 \text{ Pg C y}^{-1}$  ( $\pm 3\%$  interannual variation). Therefore,  $\sim 0.8\%$  of the overlying net primary production reaches the sea floor in the deep ocean, in agreement with previous studies (Lutz et al., 2002). In contrast, the sea floor of continental margins received  $0.62 \text{ Pg C y}^{-1}$  ( $\pm 12\%$  interannual variation). The Pace et al. (1987) relationship may not be applicable globally and factors such as ballasting influence the efficiency of organic carbon flux to the sea floor (Armstrong et al., 2002), but given the data available these results do provide a first-order approximation.

Our results indicate that POC flux to the seafloor over most of the deep sea is very small (i.e.  $< 1 \text{ gC m}^{-2} \text{ y}^{-1}$ ). The largest flux (i.e.  $> 2 \text{ gC m}^{-2} \text{ y}^{-1}$ ) occurs under major divergences (equatorial upwelling zones and upwelling areas along eastern ocean margins), under the South Atlantic and Southern Indian Ocean Currents, beneath the

north Pacific convergence, and on the continental slopes and shelves. Seamounts and substantial portions of the mid-ocean ridges show higher bottom POC flux values, especially south of Iceland ( $> 3 \text{ g C m}^{-2} \text{ y}^{-1}$ ); these topographic highs received over twice the amount of POC derived from surface production as the surrounding sea floor, because they intercepted sinking POC. Clearly, these variations may be significant for local benthic biota. The POC flux to the bottom of continental margins (values  $> 4 \text{ g C m}^{-2} \text{ y}^{-1}$ ) exceeded anything estimated for the deep ocean. Margins showed both high production and high deposition of POC.

The answer to the question of how much carbon is actually buried in marine sediments every year, is still difficult to resolve. This answer is key to understand whether the biological pump is more significant along continental margins than in the ocean's interior. Recently, it has been estimated that  $0.13\text{-}0.16 \text{ Pg C y}^{-1}$  are buried in the oceans, with 80-85% of this occurring along continental shelves and deltas (Berner, 1992; Hedges and Keil, 1995). If we assume an average of 30% POC burial rate in deep sea sediments (Jahnke, 1996) and 10% preservation on continental margins, then our calculated global organic carbon burial rate of  $0.15 \text{ Pg C}$  matches those estimates. About 60% of this organic carbon would be stored in sediments on continental margins between depths of 50 and 2,000 m.

However, sequestration occurs when organic particles reach deep waters where carbon is removed from exchange with the atmosphere for at least several hundred years, even if not buried in sediments. We estimate that  $0.52 \text{ Pg y}^{-1}$  ( $\pm 2\%$  interannual variation) reach at least 2,000 m in the deep ocean ( $\sim 1.3\%$  of POC produced in overlying surface waters). This means that nearly 90% of the carbon sequestered via the oceanic biological pump is stored in the open ocean in waters 2,000 m or deeper. In contrast, approximately 10% is sequestered on continental margins sediments.

A recent study (Gregg et al., 2003) suggested that deep ocean NPP decreased  $2.8 \text{ Pg C}$  per decade between the late 1980's and the early 2000's. This would lead to a decrease of no more than  $0.004 \text{ Pg C y}^{-1}$  of the carbon sequestered to the deep open ocean at depths of at least 2,000 m, or a total decrease of at most  $0.04 \text{ Pg C}$  over 10 years. By comparison, considering continental margins alone, nearly 7% of the NPP, or over  $0.6 \text{ Pg C y}^{-1}$ , reaches the sea floor there.

### **Publications:**

In conjunction with Frank Muller-Karger at the University of South Florida, the following manuscripts have been submitted for publication:

1. Frank Muller-Karger, Ramon Varela, Robert Thunell, Yrene Astor, Haiying Zhang, and Chuanmin Hu, 2004. Processes of Coastal Upwelling and Carbon Flux in the Cariaco Basin, *Deep-Sea Research II*, vol. 51, 927-943.
2. Frank Muller-Karger, Chuanmim Hu, Serge Andrefouet, Ramon Varela and Robert Thunell, 2004. The color of the coastal ocean and applications in the

solution of research and management problems, In: *Remote Sensing of Coastal Aquatic Environments*, R. Miller, C. Del Castillo and B. McKee, eds., Springer, 101-127

3. Frank Muller-Karger, Ramon Varela, Robert Thunell, Chaunmin Hu and John Walsh, 2004. The Importance of Continental Margins in the Global Carbon Cycle, *Geophysical Research Letters* (in press).
4. Muller-Karger, F, Ramon Varela, Robert C. Thunell, Mary I. Scranton, Gordon T. Taylor, Yrene Astor, Eric Tappa, Miguel A. Goñi, Raymond N. Sambrotto, Haiying Zhang, Baumar Marin, Chuanmin Hu, and Robert H. Weisberg, 2004, CARIACO: A Time Series of Primary Production and Vertical Export in the Cariaco Basin, In : *JGOFS Continental Margin Synthesis*, Liu and Atkinson (eds).

#### **Meeting Presentations:**

1. Thunell, R. and others, 2002, The Cariaco time series study: Climate forcing, particle fluxes and sediment accumulation, Eos 83, 124 (ASLO/AGU Ocean Sciences Meeting, Hawaii).
2. Woodworth, M., Goni, M., Thunell, R., Tappa, E. and Varela, R., 2002, Variations in stable carbon isotopes in sinking organic matter over three seasonal cycles collected as part of the CARIACO time series, Eos 83,125 (ASLO/AGU Ocean Sciences Meeting, Hawaii).
3. Preliminary Estimations of Vertical Particulate Carbon Flux: From the Cariaco Basin to Global Margins and Oceans by Frank Muller-Karger, Haiying Zhang, Chuanmin Hu, Robert Thunell, and Ramon Varela, (Ocean Color Research Team (OCRT) Meeting, April 15-17, 2003, Miami)